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A study of capacitance-voltage curve narrowing effect in capacitive microelectromechanical switches

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In this letter, we report on the capacitance-voltage (*C-V*) curve narrowing effect, which occurs in the oxide-based microelectromechanical switches that are subjected to dc bias stress for a prolonged period of time. The narrowing effect for the noncontact dc bias stress condition is shown, which proves that membrane-to-dielectric contact is not needed for narrowing to occur. It is also shown that neither mechanical degradation nor charge trapping due to dielectric conduction or air ionization is solely responsible for the *C-V* instabilities reported in the literature. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2978159]

Radio-frequency microelectromechanical capacitive switches (rf MEMSs) are high performance devices with applications in telecommunication systems.[1] The capacitance-voltage (*C-V*) curve of these devices shows thresholds at both forward and reverse biases as the switch is turned ON and then OFF at the pull-in (V_{PI}) and pull-out (V_{PO}) voltages, respectively. The *C-V* curve changes during switch operation, and this has received much attention in the literature.[2–11]

Early work showed that the forward and reverse thresholds shift in the same direction.[2,3] This is referred to as *C-V* shift and was interpreted solely as charge trapping in the dielectric (dielectric charging) during the ON state of the switch. Later work[4–7] showed another instability effect, namely, a *C-V* curve narrowing that occurs when the thresholds decrease in magnitude, as shown in Fig. 1(a) for the pull-in. This was also attributed to the ON-state dielectric charging. Additionally, in Refs. 7 and 8 it was suggested that charging can also occur before the membrane reaches the dielectric. Further study[9] has also associated the narrowing with the ON-state bias stress; however, mechanical creep was indicated as a source. Finally, recent work[10] presented experimentally that there can be two distinct mechanisms responsible for the *C-V* narrowing. These are the dielectric charging[5] and the mechanical degradation known as fatigue; moreover, their occurrence depends on the type of stress applied. This study showed that the charging dominated during dc bias stress in the ON state and exhibited almost complete reversibility with time, while the mechanical degradation dominated after repeated actuations and showed no reversibility.

The aim of this work is to investigate the *C-V* narrowing effect in oxide-based rf MEMS. The key goal is to isolate the physical mechanism responsible. We measure the *C-V* before and after the dc bias stress. However, in contrast to the previous work, which reports on the effect of contact (ON-state) bias stress, we also show the results for the noncontact (OFF-state) bias stress condition. Therefore, we can eliminate the effects of mechanical degradation due to fatigue/creep and charge trapping due to dielectric conduction or air ionization during the stress time on the *C-V* variation. In this letter only the pull-in thresholds are shown. However, similar characterization can be used for the pull-out analysis.

The switches used in this work are 100×100 and 200×200 μm^2 aluminum membranes suspended 1.5 μm above a coplanar waveguide (CPW) line that is coated with 130 nm plasma-enhanced chemical-vapor deposition SiO_2. Due to process variation the pull-in varies across the wafer with a standard deviation of 1.2 V over ten random devices. The

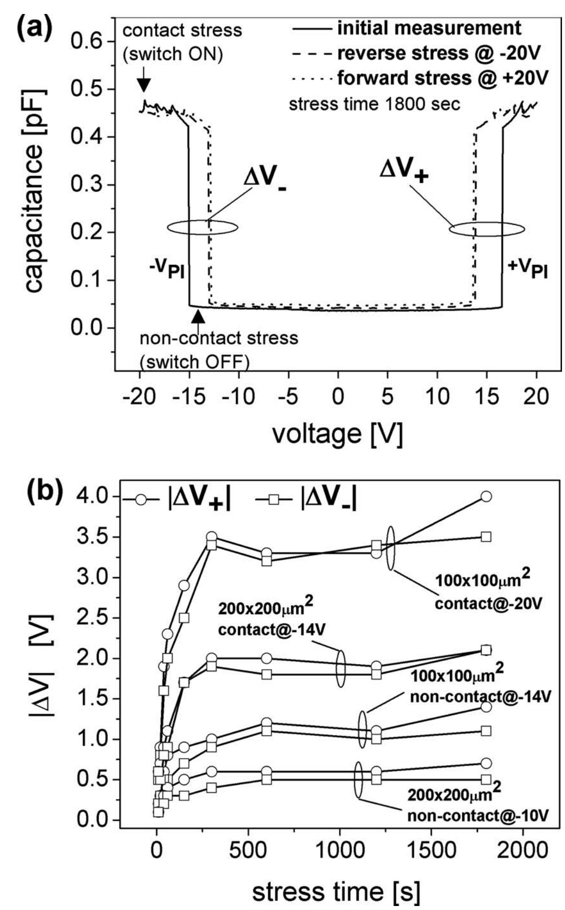

FIG. 1. (a) The narrowing effect for the reverse (−20 V) and the forward (+20 V) contact stress applied for 1800 s, relaxation time between each stress polarity was 1 h, 100×100 μm^2 switch. (b) Full narrowing characteristics for the reverse contact and noncontact stress conditions (note that a single polarity stress results in a decrease in pull-in of both polarities). Similar results were obtained for the forward stress. Each pair of $|\Delta V_+|$ and $|\Delta V_-|$ at a given stress time is measured on a different device.

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mean reverse and forward pull-ins are −16, +18, and −12, +14 V for 100×100 and 200×200 μm^2 devices, respectively. The difference between the reverse and forward values arise from the process-induced charge in the dielectric.[11] The measurements are performed using an Agilent B1500A and by wafer probing on Cascade Summit-1200 station in dry environment and at room temperature. A bias is applied between the membrane and the CPW and at the reverse bias the voltage at the membrane is negative and vice versa for the forward bias. A typical time for a single pull-in measurement is in the range of 1–2 s.

Figure 1(a) shows a typical *C-V* narrowing effect after contact bias stress. We compare the initial *C-V* curve with that after reverse (−20 V) and forward (+20 V) stresses applied for 1800 s. During this experiment the mechanical and electrical stresses occur simultaneously. Thus, it is difficult to distinguish which stress type is the cause of the narrowing effect. In addition, it is not clear if membrane-dielectric contact is needed for this instability to occur.[7,8] Moreover, measurement technique that relies on switch actuation may also stress the device, hence causing the *C-V* variation itself.

We believe that solely using contact bias stress methods is not an adequate attempt to identify the physical mechanism responsible for the narrowing effect. Therefore, we propose the noncontact bias stress technique. In this technique the applied voltage is lower than the pull-in, and the switch remains open during the stress time, as indicated in Fig. 1(a). Thus, we can separate the influence of the mechanical and electrical stresses on the *C-V* narrowing effect.

The comparison of narrowing results after the noncontact and contact reverse bias stresses is shown in Fig. 1(b). Similar measurements were performed for the forward stress and no polarity dependency was observed [see Fig. 1(a)]. The measurement procedure was as follows: first, the initial forward and reverse pull-ins are measured by the voltage sweep from 0 to +20 V and then from 0 to −20 V. Second, the reverse dc bias stress in the contact or noncontact condition is applied for a period of time called a stress time. Finally, another forward and reverse pull-ins are measured, and the induced pull-in change $|\Delta V|$ is calculated. This is repeated for different stress times. In the case of the contact stress the biases are −20 and −14 V for 100×100 and 200×200 μm^2 devices, respectively. For the noncontact characteristics the bias stresses are set at a level of 2 V below the initial pull-in and are approximately −14 and −10 V, respectively. Note that each pair of $|\Delta V_+|$ and $|\Delta V_-|$ at a given stress time is measured on a different device to exclude the accumulation of the electrical and mechanical stresses. The results are shown for two different levels of the reverse bias stress at each stress type.

During the noncontact stress no mechanical degradation can occur as the mechanical load on the membrane is insignificant. The dielectric charging due to air ionization[12] and current conduction[13] can also be ignored as the field across the switch electrodes remains only 0.1 MV/cm. In general, during the contact stress condition the mechanical degradation of the membrane and the charge trapping due to dielectric conduction are possible to occur. Moreover, if the air gaps related to the surfaces roughness are sufficiently small after the switch closure, they can reach a high field that can produce an air ionization and subsequent charge deposition at the dielectric.[14] However, to minimize the influence of both charging mechanisms the structures were fabricated for high roughness of contacting surfaces. The down state contact of the membranes was characterized by the optical and capacitance measurements.[15] It was found that the residual airgap is in the range from 160 to 240 nm, which depends on the applied voltage level. At the contact stress of 20 V used in this work, the airgap is 230 nm,[15] thus the field still remains low and air ionization is unlikely to occur.[12] Moreover, the effect of charge trapping mechanism is also minimal as the current conduction is limited only to the few membrane-dielectric contact points. Therefore, during the contact stress condition and due to the high roughness of contacting surfaces, most of the dielectric area is exposed to the stress similar as used during the noncontact condition. Thus we propose that there is a common physical mechanism for both stress conditions, which is dominated by the mechanism occurring in the noncontact region. This theory is supported by the data described in Fig. 1(b). It shows that regardless of stress condition (contact or noncontact), single polarity stress results in a decrease in pull-in of both polarities, hence causing the narrowing effect. Note that the forward and reverse changes are similar in magnitude. The narrowing after the contact stress is larger as the field across the oxide is higher due to around five times smaller air gap.

To prove that the measurement sweep itself has no dominant effect on the narrowing obtained after the noncontact stress and the results can be attributed to stress mode only, we investigate the self-actuation properties of the switch. In this experiment we apply the noncontact stress as shown before, however, now we measure the capacitance versus time. In Fig. 2(a) a typical result for two devices of which one was reverse −14.4 V and the second forward +16.2 V biased are shown. The pull-ins were measured prior to the experiment and are −15.4 and +17.2 V, thus $|\Delta V|$ is 1 V. The sharp increase in the capacitance after a period of time indicates that the membrane collapses on the dielectric; the switch self-actuates. Figure 2(b) describes full self-actuation characteristic for forward and reverse biases, where $|\Delta V|$ is plotted versus time to self-actuation. Note that each measurement point was performed on a different device. We can observe that the magnitudes of $|\Delta V|$ after the noncontact stress condition in Fig. 1(b) are slightly lower when compared to the self-actuation data in Fig. 2(b). This is due to the fact that the stress voltage was also lower ($|V_{PI}|-2$ V) in comparison to the self-actuation experiment ($|V_{PI}|-|\Delta V|$). This was necessary to avoid the self-actuation of the switch during the noncontact stress application. It is clear that the $|\Delta V|$ induced during the self-actuation experiment can be attributed to bias stress mode only. It is also observed that the self-actuation curves and those after the noncontact stress exhibit similar magnitude of $|\Delta V|$ and saturation time of characteristics. These similarities indicate that the results of the narrowing after the noncontact stress can also be attributed to the stress mode, with no significant effect of the measurement sweep.

The experimental data in this work strongly suggest that a common physical mechanism is responsible for the narrowing effect (after contact and noncontact stresses) and self-actuation phenomena on the switches investigated (with rough contacting surfaces). As previously stated, the mechanical degradation cannot occur during the self-actuation and noncontact experiments. In addition, previous work on aluminum switches showed that the contact stress used in

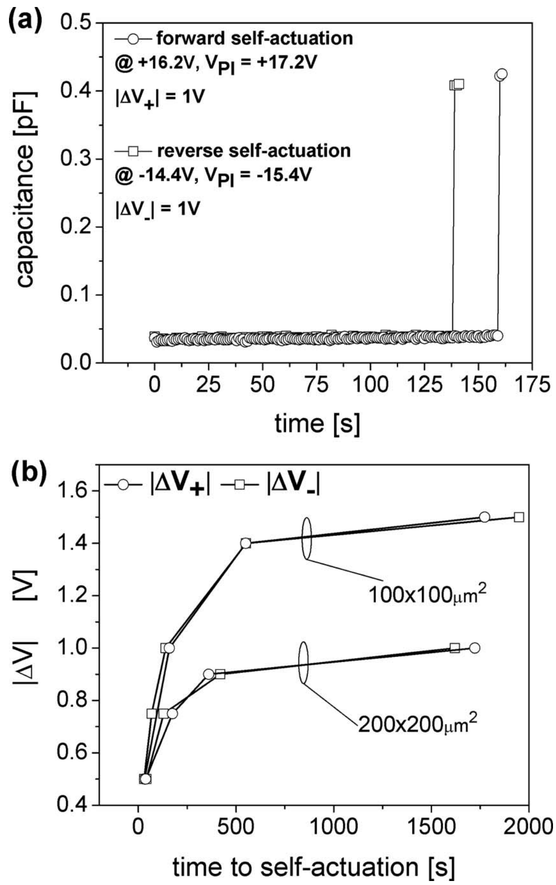

FIG. 2. (a) The self-actuation phenomena for two 100×100 μm^2 switches of which one was reverse (−14.4 V) and second forward (+16.2 V) biased, self-actuation occurs at 140 and 160 s, respectively. (b) Full self-actuation characteristics for reverse and forward bias polarities. Each point of characteristics at a given $|\Delta V|$ is measured on a different device.

this work (i.e., stress time, ambient temperature, and stress voltage magnitude) cannot cause significant mechanical degradation of the membrane.[9,10] Moreover, from the self-actuation experiment we can observe that the physical mechanism is independent of the stress voltage polarity. This strongly indicates that the charge trapping (uniform or nonuniform) due to dielectric conduction or air ionization is not the physical mechanism responsible. Furthermore, we have also shown that air ionization and dielectric conduction is unlikely to occur as the field in all of the three experiments is very low.

Because the electrode limited mechanisms (mechanical degradation, charge trapping due to dielectric conduction, or air ionization) can be eliminated as potential causes of the narrowing effect, we can infer that an intrinsic physical mechanism associated with the dielectric media is the root cause. Previous research[16] has indicated that the intrinsic dielectric polarization via space charge mechanisms also known as interfacial polarization,[17] which has a response time of 0.001 to thousands of seconds,[18] is the cause of the self-actuation phenomena. In this mechanism, upon the application of bias mobile charges of opposite polarity to the membrane drift through the dielectric and accumulate at the dielectric-air interface. In MEMS devices, the charge at this interface has the largest influence on the field in the air gap.[2] As a result, the electrostatic force in the air gap increases over a time to the value greater than that required to pull-in the switch, which cause its self-actuation. In other words, the pull-in lowers in magnitude after the stress application.

Although this classical model of uniform dielectric polarization can explain the self-actuation behavior observed in this work, it cannot account for the narrowing effect. A sheet charge opposite polarity to the stress voltage is assumed to accumulate at the dielectric-air interface during the stress. It is clear that such charge can reduce the pull-in for the bias voltage of the same polarity as the stress voltage (i.e., forward direction) and can also cause the self-actuation. However, it would be expected that the pull-in in the reverse direction would equally increase in magnitude rather than decrease [as seen in Figs. 1(a) and 1(b)], assuming that this accumulated charge retains its polarity during the reverse pull-in sweep. Therefore we propose that more complex intrinsic polarization process is occurring and that the simple one-dimensional metal-air-dielectric-metal model[16] of the switch may not be sufficient to explain the cause of the narrowing effect.

In conclusion, we investigated the *C-V* curve narrowing effect in the oxide-based MEMS switches, which are subjected to dc bias stress. In contrast to work reported previously, we showed the narrowing effect for the noncontact stress condition, which proves that membrane-to-dielectric contact is not required for the narrowing to occur. This work also showed that neither the mechanical degradation nor charge trapping due to dielectric conduction or air ionization is responsible for the narrowing observed in our switches with rough contacting surfaces.

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